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NOLTR 65-1

INITIATION OF EXPLOSIVES BY EXPLODING WIRES

31 MARCH 1965

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 65-1

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

VI. Further Effects of Wire Material on the Initiation of PETN by Exploding Wires

By

Howard S. Leopold

ABSTRACT: Silver, copper, and iron wires were investigated as possible bridgewire materials. The wires were exploded by a 1-microfarad capacitor charged to 2,000 Volts. Wire materials that give high peak powers are favorable for effecting detonation. Low boiling point, low heat of vaporization metals such as silver and copper permit greater energy transfer to an explosive than high boiling point, high heat of vaporization metals such as iron

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EXPLOSION DYNAMICS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

INITIATION OF EXPLOSIVES BY EXPLODING WIRES
VI. FURTHER EFFECTS OF WIRE MATERIAL ON THE INITIATION OF PETN BY EXPLODING WIRES

This report is Part VI of an investigation concerning the initiation of explosives by exploding wires. The work was performed under Task RUME-4E000/212-1/F008-08-11 PA 019, Analysis of Explosive Initiation.

The results should be of interest to personnel engaged in initiation research and design of exploding bridgewire ordnance systems.

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R. E. ODENING
Captain, USN
Commander

C J Aronson

C. J. ARONSON
By direction

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INTRODUCTION

1. This report is the sixth in a series describing experimental results obtained from an investigation of exploding bridgewires. A previous investigation, reference 1* had indicated that the detonation of high explosives could be effected more readily by those wire materials capable of absorbing energy from the power supply at a high rate and which were brought to the vapor state by the least quantities of energy. Aluminum and gold (Class I materials with low boiling point and low heat of vaporization), reference 2, were found able to effect detonation in PETN under more difficult conditions than platinum and tungsten (Class II materials with high boiling point and high heat of vaporization).

2. The present investigation was concerned with verifying the extrapolations made from the study of the previous materials i.e., aluminum, gold, platinum, and tungsten. Various lengths of silver, copper, and iron wire were evaluated for their ability to effect detonation in PETN and compared with each other. On the basis of extrapolations made from the first four materials tested, silver (Class I) would be expected to be the best of the three materials, followed respectively by copper (Class I) and iron (Class II). Very low melting point metals were not considered for possible use in electroexplosive devices because of their unfavorable mechanical properties.

ELECTRICAL CIRCUITRY

3. A typical exploding bridgewire circuit for ordnance purposes uses a 1-microfarad capacitor charged to 2,000 volts. The actual test circuit used for this investigation is shown in Figure 1. The transmission line was kept as short as possible consistent with the necessity for testing in an explosive firing chamber. The parameters for the test circuit were:

$$C = 0.97 \text{ microfarad}$$

$$L = 0.58 \text{ microhenry}$$

$$R = 0.35 \text{ ohm}$$

$$V_o = 2,000 \text{ volts}$$

* References and other reports in this series are listed on Page 7.

TEST PROCEDURE

4. Various lengths of silver, copper, and iron bridgewires were compared for their ability to effect detonation in PETN. The test fixture and experimental methods described in reference 3 were used for observing the growth of explosion. The ability of the wire to effect detonation was gradually decreased by increasing the density of the PETN in contact with the wire. This method was used to determine the most advantageous wire material and its optimum length. Current and voltage waveforms, and the derived resistance, power, and energy values were examined to help interpret the experimental results.

EXPERIMENTAL RESULTS

5. A test series was run with each bridgewire material. A 2-mil diameter wire was used for each material and the wire lengths ranged from 0.0125 to 0.100 inch. An examination of tables 1, 2, and 3 shows that silver and copper bridgewires are almost equally effective in detonating PETN, with iron bridgewires a poor third. Various electrical and physical attributes of the three bridgewire materials were then examined.

6. Examination of the current waveforms shown in figures 2, 3, and 4 shows that the different materials explode on different portions of the current pulse. (To aid in this one visualizes the current burst to the wire as a portion of the sine wave current which would be obtained if the wire were replaced by an electrical short.) Silver wires burst approximately two thirds up the leading edge of the current pulse. Copper wires burst somewhat nearer to the current pulse peak exhibiting less of a resurge than the silver wires. The various iron wires gave a wide current burst dispersion which seems to be typical of Class II materials. The optimum length of iron wire for effecting detonation explodes approximately half way up the leading edge of the current pulse. The current drop at burst is slower for iron than for the Class I materials.

7. Examination of the voltage waveforms in figures 5, 6, and 7 shows higher voltage peaks for the Class I materials than for iron. For all three materials, the 0.100-inch length gave the highest peak voltage. In general, the peak voltage spikes of the Clara I materials tend to be of higher value and shorter duration than those of the Class II materials. Iron showed the

vaporization plateau characteristic of Class II materials and gave the lowest peak voltages of the seven materials evaluated to date.

8. Examination of the resistance curves in figures 8 and 9 for silver and copper shows a smooth rapid rise for both metals to the peak resistance value. Copper exhibited irregular resistance fluctuations just after the peak resistance, whereas the other six elements evaluated tended to give smooth resistance drops in this region. Copper had the lowest peak resistance of the seven elements evaluated. Iron, in figure 10, shows the definite resistance plateau typical of Class II materials before the peak resistance occurs.

9. Comparison of figure 11, 12, and 13 shows that the delivery of power was higher for the Class I materials, silver and copper. The highest peak power was observed with 0.100-inch long copper wire. The wire length which gave the highest power for each of the three materials was longer than the optimum length for effecting detonation. Iron had the lowest power rate of the seven materials evaluated.

10. All three materials show a small energy deposition during the first 0.3 microsecond. See figure 14, 15, and 16. The energy deposition remained low for the first 0.6 microsecond for the high conductivity metals, silver and copper. Silver and copper give a sigmoidal type of energy-time curve similar to the other metals previously tested. Iron shows a different energy-time relation than the other metals, with the rate of energy deposition tending to be more constant than sigmoidal.

DISCUSSION

11. Previous testing with aluminum, gold, platinum, and tungsten wires had indicated that the more efficient wire materials for effecting detonation have lower energy requirements for vaporization and high rates of energy deposition in the fixed firing circuit.[1] The results with silver, copper, and iron wires were found to conform closely to the results of these previous tests. All the Class I materials tested (aluminum, gold, silver, and copper) were found to be better for effecting detonation than any of the Class II materials (platinum, tungsten, iron). Trouton's rule that the heat of vaporization in calories is approximately equal to 21 times the temperature of vaporization (boiling point) indicates that no crossover should be expected between the two classifications.

12. The electrical characteristics help explain the superiority of the Class I materials in effecting detonation. The series RLC circuit used for exploding the wires has for its differential equation

$$L \frac{di}{dt} + Ri + \frac{q}{c} = 0 \qquad (1)$$

where L = inductance, i = current, R = resistance, q = charge, c = capacitance, and t = time. It was previously shown[3] that the initial rate of rise of current is governed by

$$\frac{di}{dt} = \frac{V_o}{L} \quad t \to 0 \qquad (2)$$

where V_o is the initial voltage. As long as the Ri term in (1) remains negligible during the initial current rise, the current rise will be mainly governed by (2) since $q = CV_o$. Class I materials such as silver, have an initial small resistance value which remains low until a rapid resistance rise occurs at burst. Figure 17 shows the composite traces for the 0.050-inch length silver wire. The resistance trace shows roughly a ten fold increase from the original value of 0.022 ohm during the first 0.6 microsecond. This permits the current rise to be governed mainly by equation (2) for a relatively long period of time. Class II materials such as iron tend to have higher initial resistances and initially absorb energy at a faster rate. Figure 18 shows the composite traces for the 0.050-inch length iron wire. The resistance trace in figure 18 shows a fast rise until vaporization occurs, at which time the resistance tends to remain constant at 1.05 ohms. At approximately the time the vaporization plateau commences, one observes an inflection in the current; further lowering the rate of rise. This inflection is thought to show the increasing influence of the Ri term. It can be seen that Class I materials tend to permit a higher current density, enhancing the pinch effect. Peak power occurs at a time when the current is decreasing and the resistance is rapidly rising. The higher current levels in the Class I materials help to give higher peak power (i^2R) since the current effect is squared.

13. Class II materials, show a greater resistance effect with increased length because their resistivity is higher. There is a much greater dispersion of the current value at burst over the experimental length range for the Class II than for the Class I materials. Compare figure 2, 3, and 4. Information on the resistance of the lower melting elements in the liquid phase is readily available.[4] Such information is fairly sparse for the higher melting metallic elements because of experimental difficulties. In general, resistivity increases

more slowly with temperature in metals in the liquid than in the solid state.[5] The resistance of iron, platinum, and tungsten appears to be almost independent of temperature in the liquid state, indicating much smaller temperature coefficients of resistivity than those of the Class I materials. The marked increase in electrical resistivity at the time of burst has been explained by a vaporization wave proceeding inward from the wire surface, reducing the conducting cross section of the wire.[6] The wave velocity depends not only on the specific energy, but also on the heat of vaporization.

14. If the wire materials evaluated are listed according to increasing energy required for complete vaporization, the following order is obtained:

$$Ag<Al<Au<Cu<Fe<Pt<W$$

The first four metals belong to Class I; the last three metals belong to Class II. If heat of vaporization of the wire material was the predominent property in regard to effecting detonation in PETN, silver should be the best material with the others following in the order shown. However, actual tests reveal the ordering to be as follows for effecting detonation with the optimum length for each material:

$$Au>Ag^{*}Cu>Al>Pt>W>Fe$$

showing other factors are involved in determining the optimum material. The ordering in each classification for the wire lengths of interest appears to be influenced strongly by the peak power. Gold, which exhibits the highest peak power over the lengths of interest in Class I, tends to be the best material for effecting detonation except in the very short lengths (<0.025-inch) where the peak power drops below those of some of the other materials. Aluminum has the lowest peak powers in Class I over the 0.025 to 0.100-inch length range. For the wire materials at their optimum length, the ordering corresponds closely to the order of decrease in peak power. However, the correlation between peak power and the ability to detonate does not exist in general. For example, the peak power for silver and copper is higher at lengths of 0.075 inch and 0.100 inch than it is at 0.050 inch, the optimum length. In the length range from 0.025 to 0.100 inch for the Class II materials, the peak powers for platinum are higher than those of tungsten which in turn are higher than those of iron. Iron, which requires the least energy for vaporization, is the poorest of the three Class II materials for effecting detonation. This shows that for the given conditions, peak power may be relatively more important than the heat of vaporization.

* Silver and copper were about equal in their ability to initiate PETN.

15. Gold exhibits the highest peak power since in addition to having a high current density at burst, gold also has the highest dwell resistance of the seven materials. Platinum has a lower current density at burst, but a relatively high dwell resistance making it one of the better Class II materials. Iron with both a lower current density and a lower dwell resistance had the lowest peak power and was the poorest for effecting detonation of PETN. It appears as though the inherent resistivity and character of the resistivity changes of the wire material are relatively more important than the energy required for vaporization.

16. A low energy requirement for vaporization appears to be a helpful adjunct to the higher peak powers typical of Class I materials. A comparison of the total energy supplied up to shortly after burst to comparative lengths of the different wire materials of both classes shows only minor variations between the metals. Energy in excess of that required for vaporization can be expected to further heat the plasma and/or vapor and also strengthen the shock and kinetic energy transfer to the explosive.

17. The necessity for initiating a critical volume of explosive is again indicated by these experiments. Tungsten wires in the liquid state before burst would be expected to have a greater temperature differential between the wire and the explosive in contact with the wire than would gold wires. Temperature differentials, however, at this time appear to be of no importance because of the limited amount of explosive in contact with the intact wire. Indications are that the wire length of the higher resistivity materials (Class II) should be shortened to reduce the resistance and permit a higher current density, thus giving a higher peak power per unit length. However, the necessity for initiating a critical volume of explosive appears to nullify any further gains by this means once a certain minimum length is reached. The experimental results do show that the optimum lengths of Class II metals for effecting detonation are shorter than those of Class I metals.

CONCLUSIONS

1. Silver and Copper (Class I) are better than iron (Class II) for effecting detonation in PETN.

2. Class I materials (compared to Class II materials) permit a higher current density before burst, allowing a greater rate of energy deposition. This coupled with the lower energy requirement for complete vaporization should allow greater energy transfer to the surrounding explosive.

3. Peak power was found to correlate closely with the ability to detonate PETN when the wire materials were at their optimum length, although this correlation is shown not to be a general one.

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OTHER REPORTS IN THIS SERIES

1. Reference 3 above

2. II Effect of Circuit Resistance on the Initiation of PETN by Exploding Wires, NOLTR 63-244

3. III Effect of Wire Diameter on the Initiation of PETN by Exploding Wires, NOLTR 64-2

4. IV Effect of Wire Length on the Initiation of PETN by Exploding Wires, NOLTR 64-61

5. Reference 1 above

TABLE 1 Effect of Bridgewire Length (Silver, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length (inch)	Density of PETN (g/cm^3) 1.15 D	1.15 L	1.2 D	1.2 L	1.225 D	1.225 L
0.025	2	0	0	2		
0.050	2	0	2	0	0	2
0.075	2	0	1[a]	1	0	2
0.100	2	0	0	2		

a Unsymmetrical growth to detonation

D = Detonation

L = Low order

TABLE 2 Effect of Bridgewire Length (Copper, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length	Density of PETN (g/cm^3)							
	1.1		1.15		1.2		1.225	
(inch)	D	L	D	L	D	L	D	L
0.025	2	0	2	0	0	2		
0.050	2	0	2	0	2	0	0	2
0.075	2	0	2	0	1[a]	1	0	2
0.100	2	0	2	0	0	2		

a Unsymmetrical growth to detonation

D = Detonation

L = Low order

TABLE 3 Effect of Bridgewire Length (Iron, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length	Density of PETN (g/cm^3)					
	1.0		1.1		1.125	
(inch)	D	L	D	L	D	L
0.0125	2	0	0	2		
0.025	2	0	1	1	0	2
0.050	2	0	1	1	0	2
0.075	2	0	0	2		
0.100	1	1	0	2		

D = Detonation

L = Low order

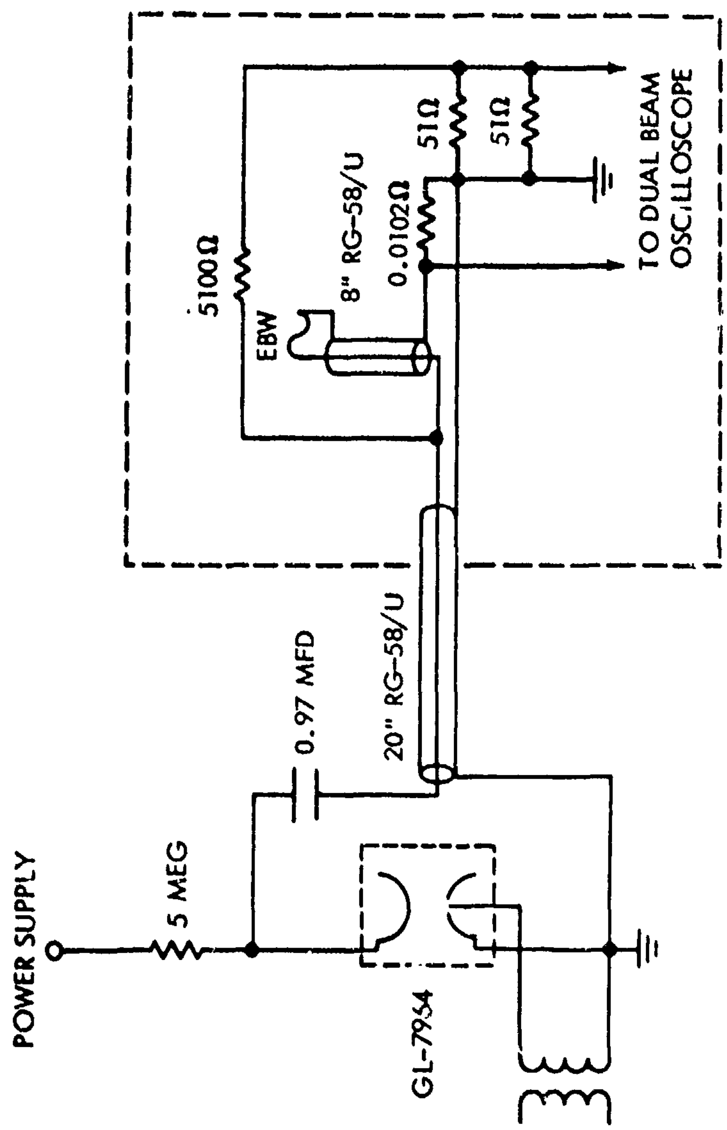

FIG. 1 TEST CIRCUIT

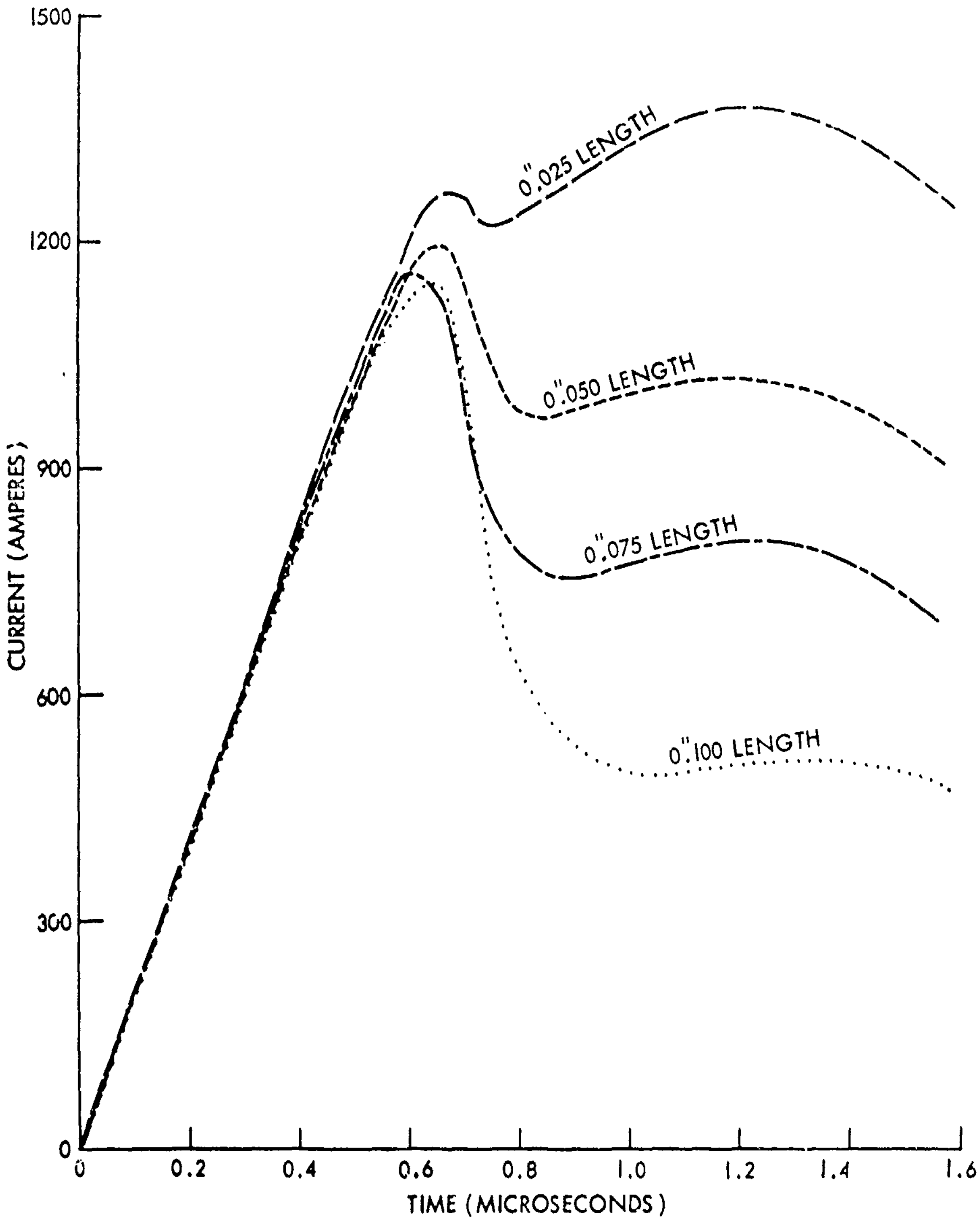

FIG. 2 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER SILVER WIRE

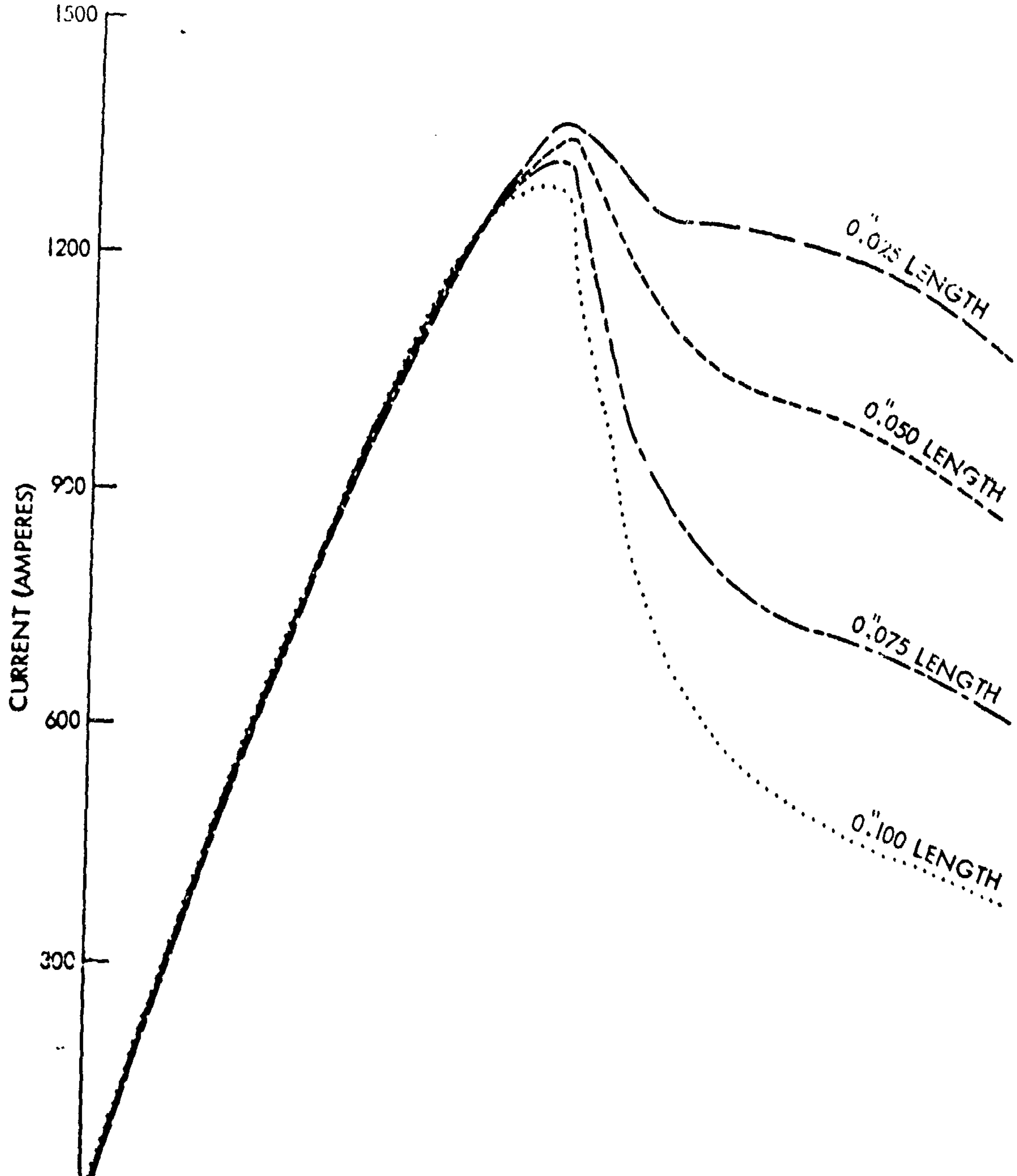

FIG. 3 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER COPPER WIRE

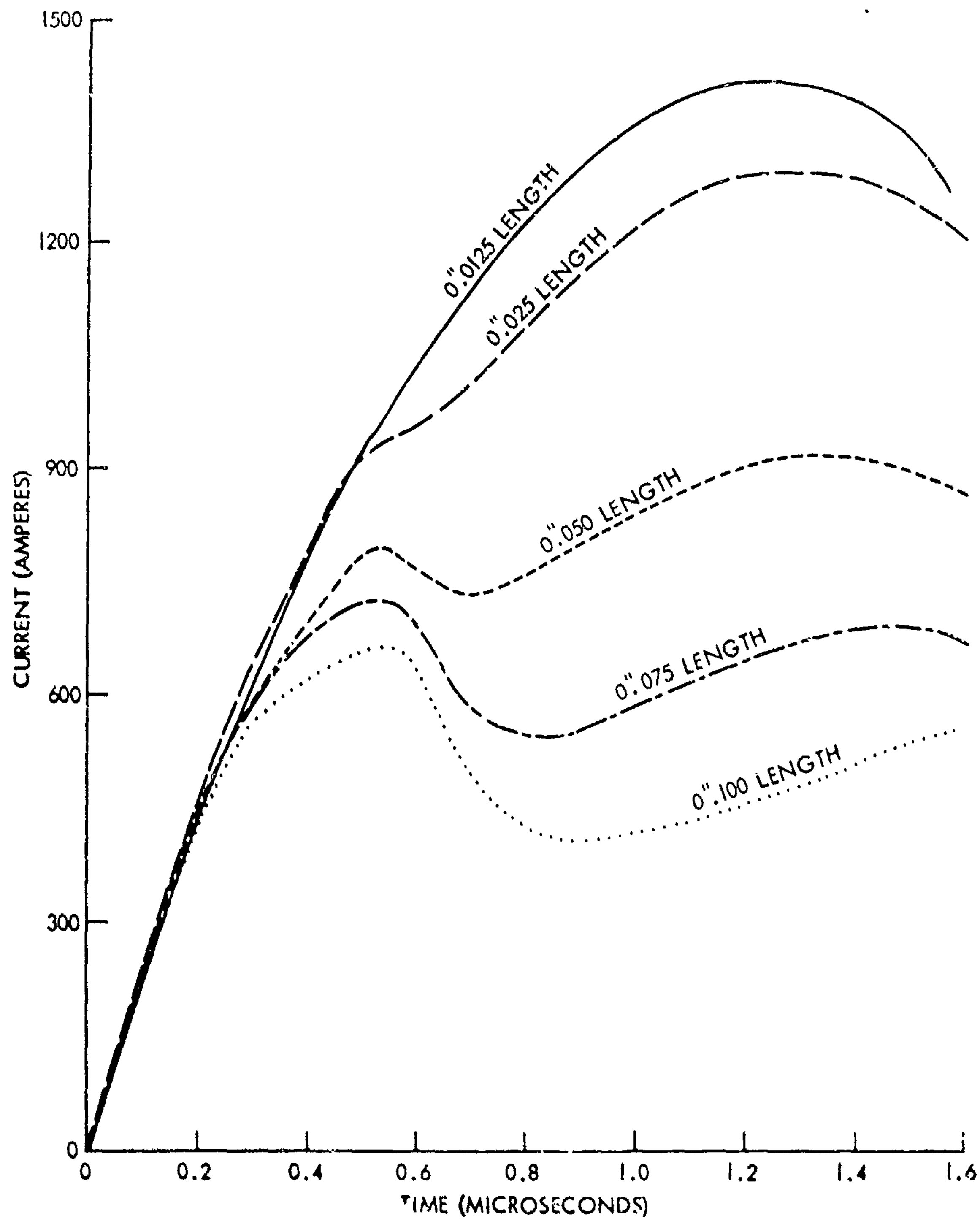

FIG. 4 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER IRON WIRE

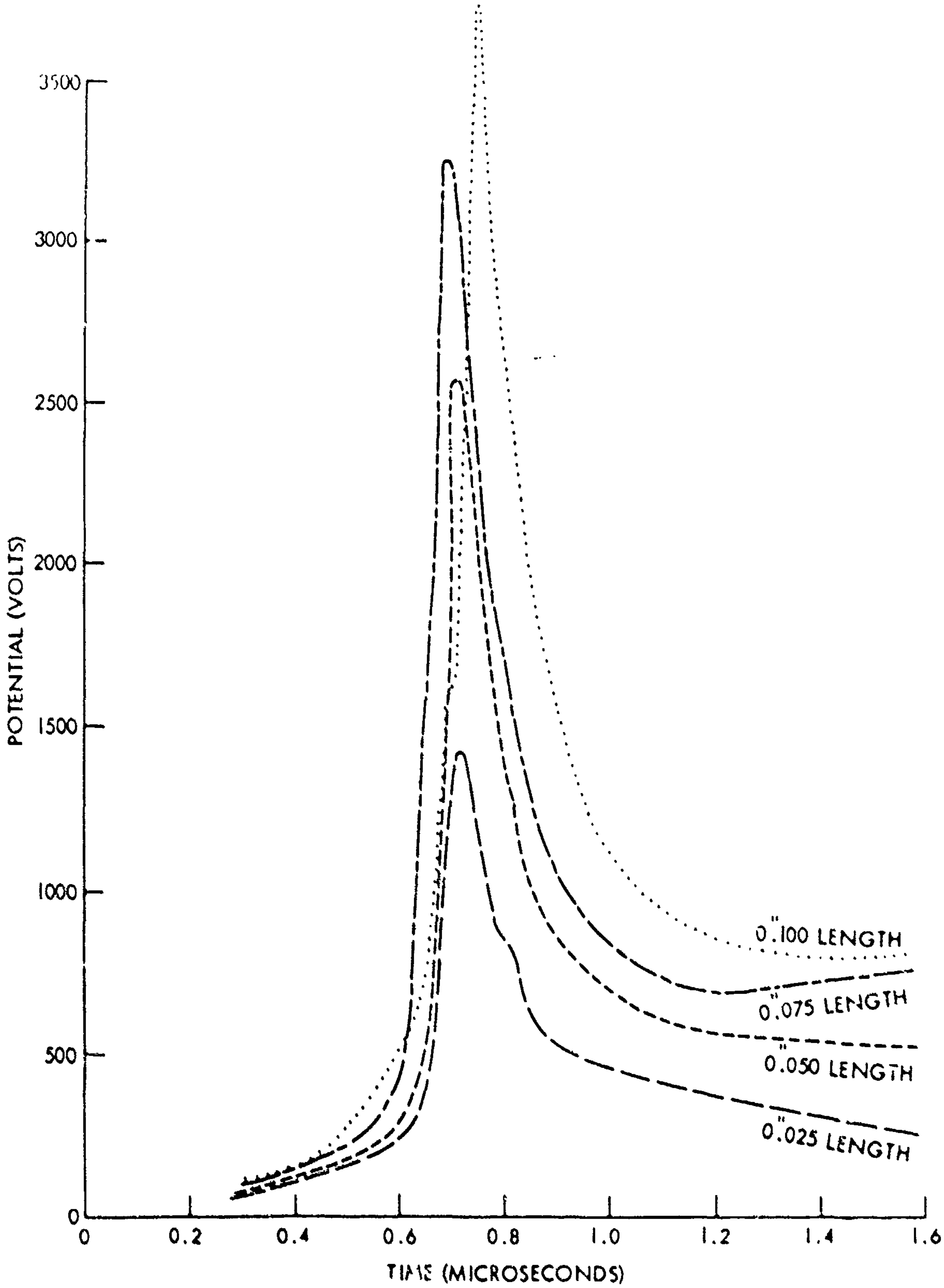

FIG. 5 VOLTAGE ACROSS VARIOUS LENGTH SILVER WIRES

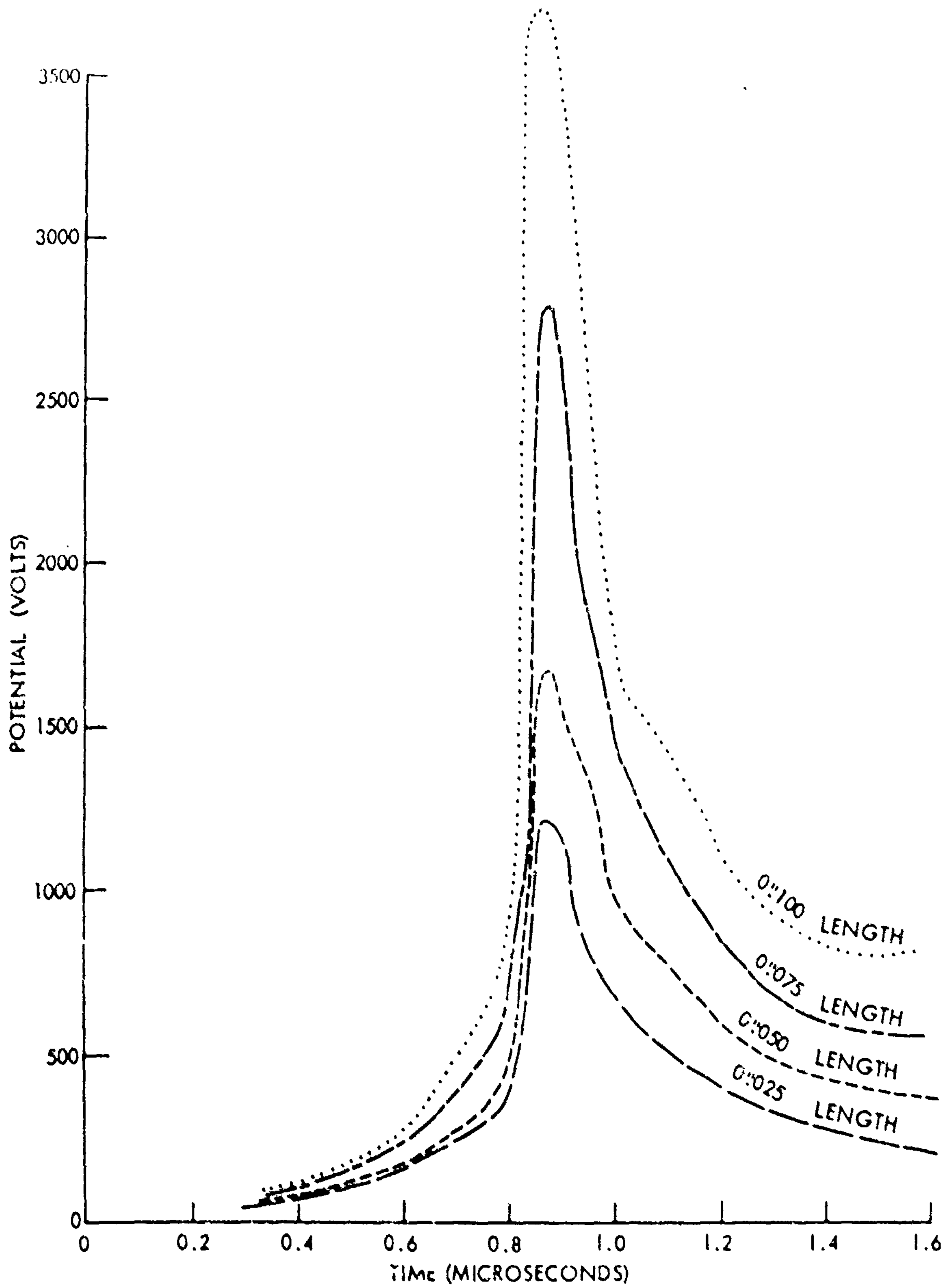

FIG. 6 VOLTAGE ACROSS VARIOUS LENGTH COPPER WIRES

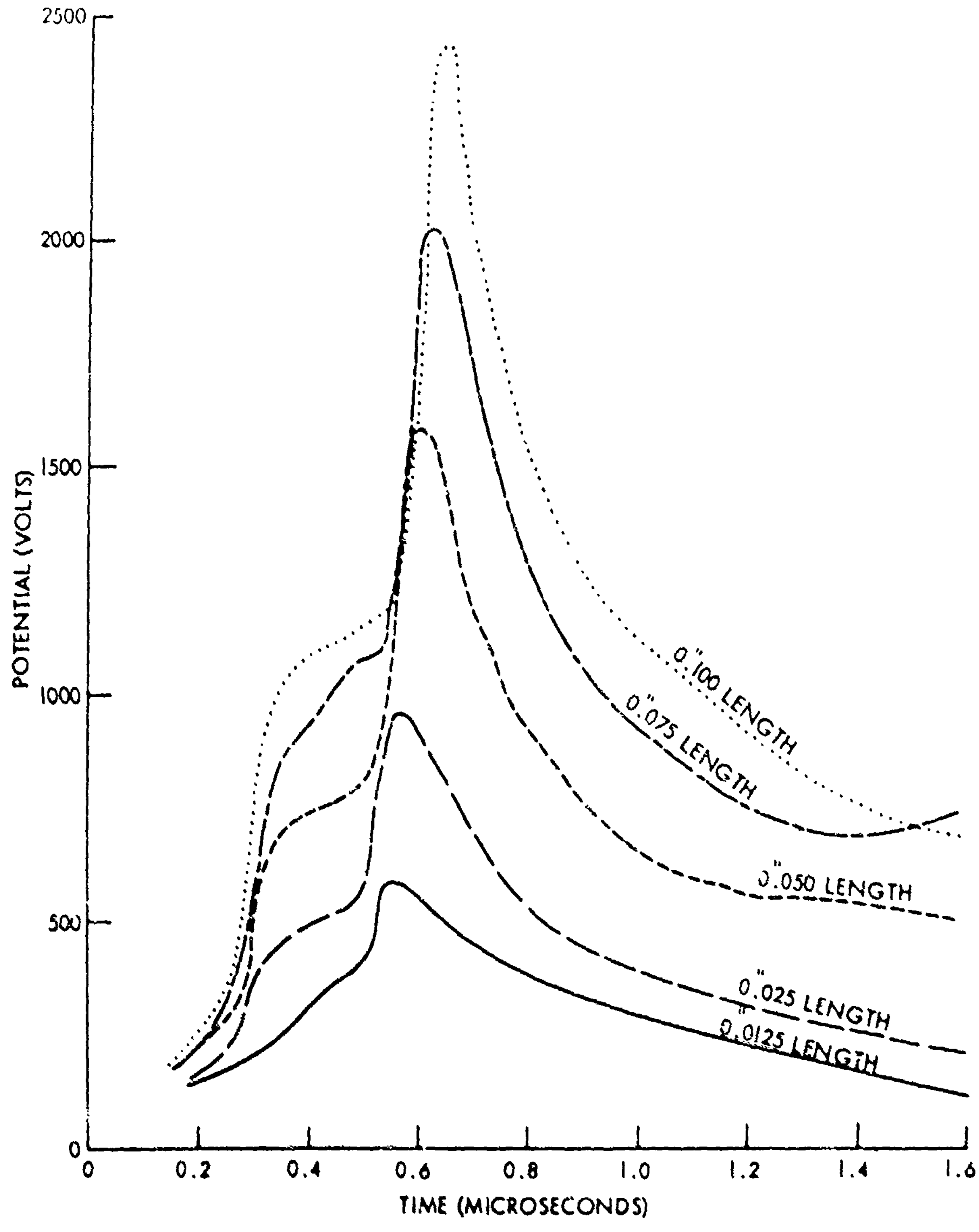

FIG. 7 VOLTAGE ACROSS VARIOUS LENGTH IRON WIRES

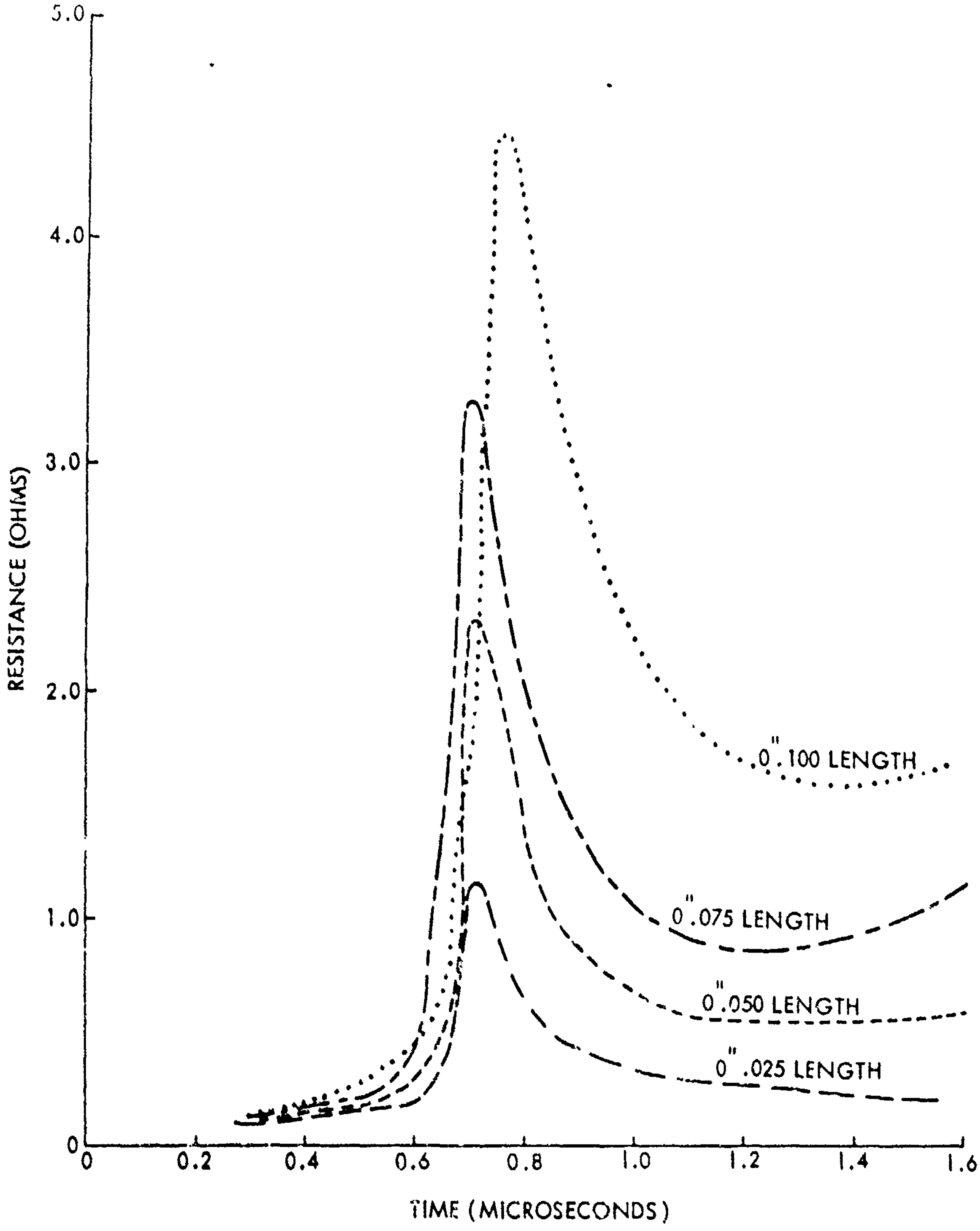

FIG. 8 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL SILVER WIRE

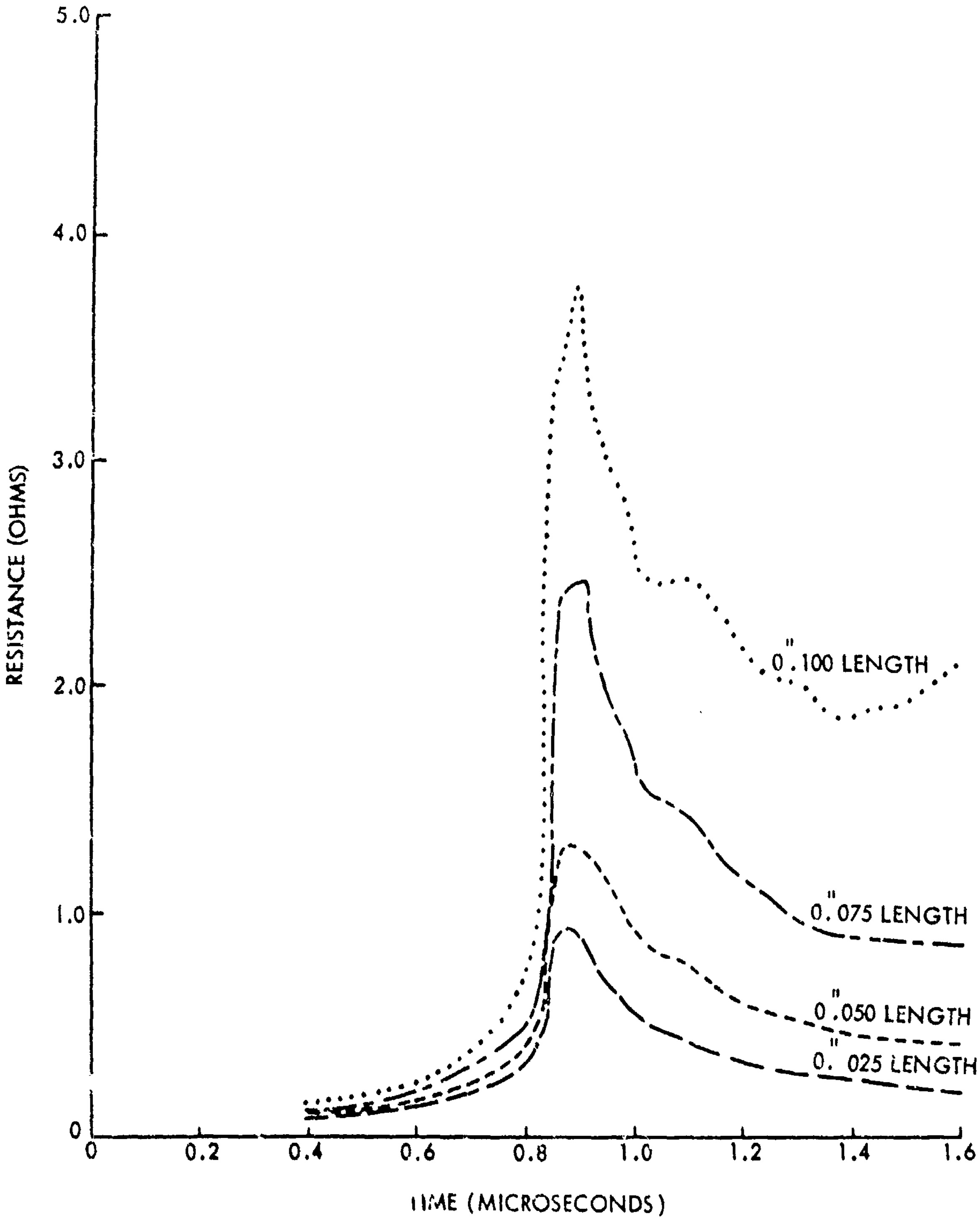

FIG. 9 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL COPPER WIRE

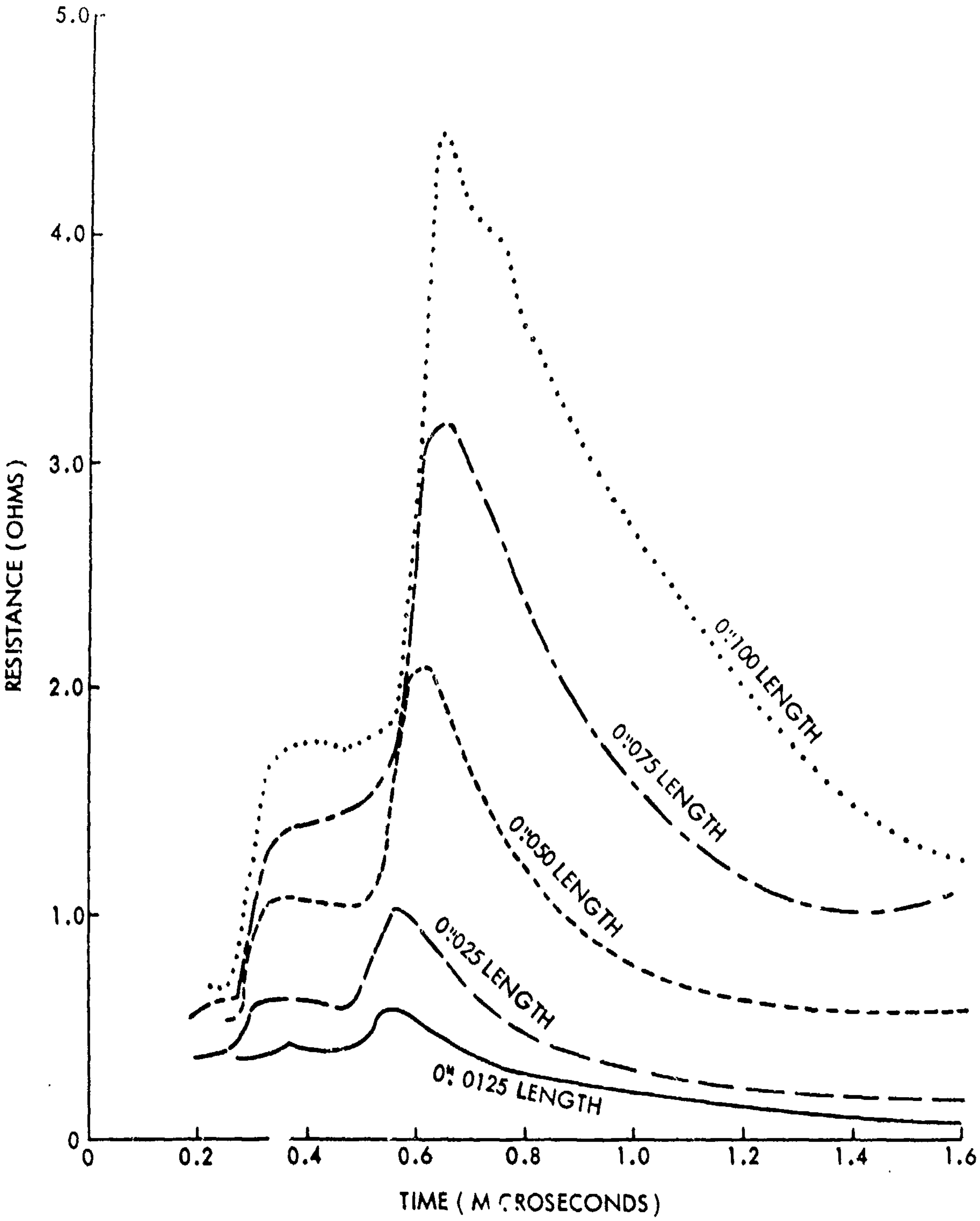

FIG. 10 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL IRON WIRE

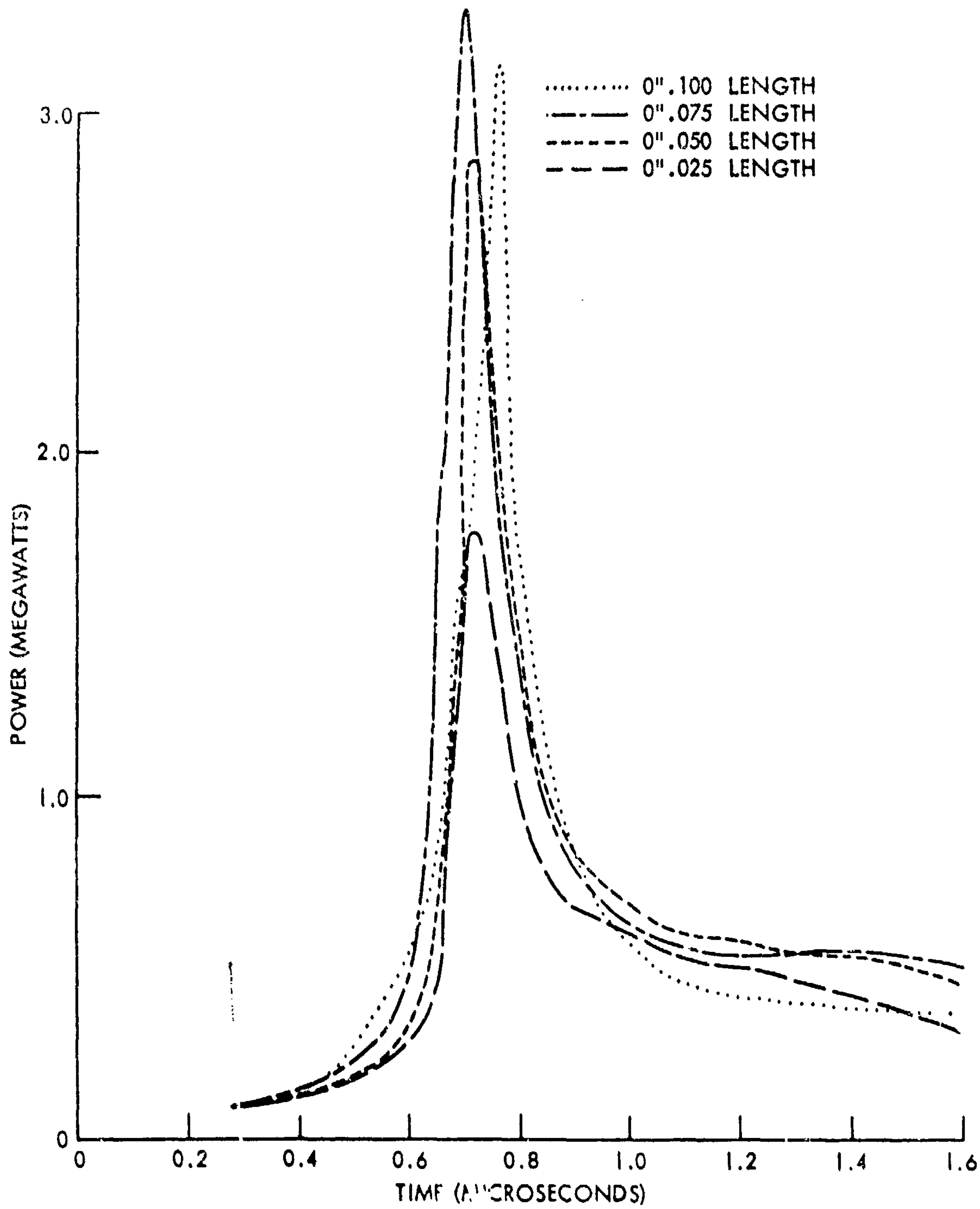

FIG. 11 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER SILVER WIRE

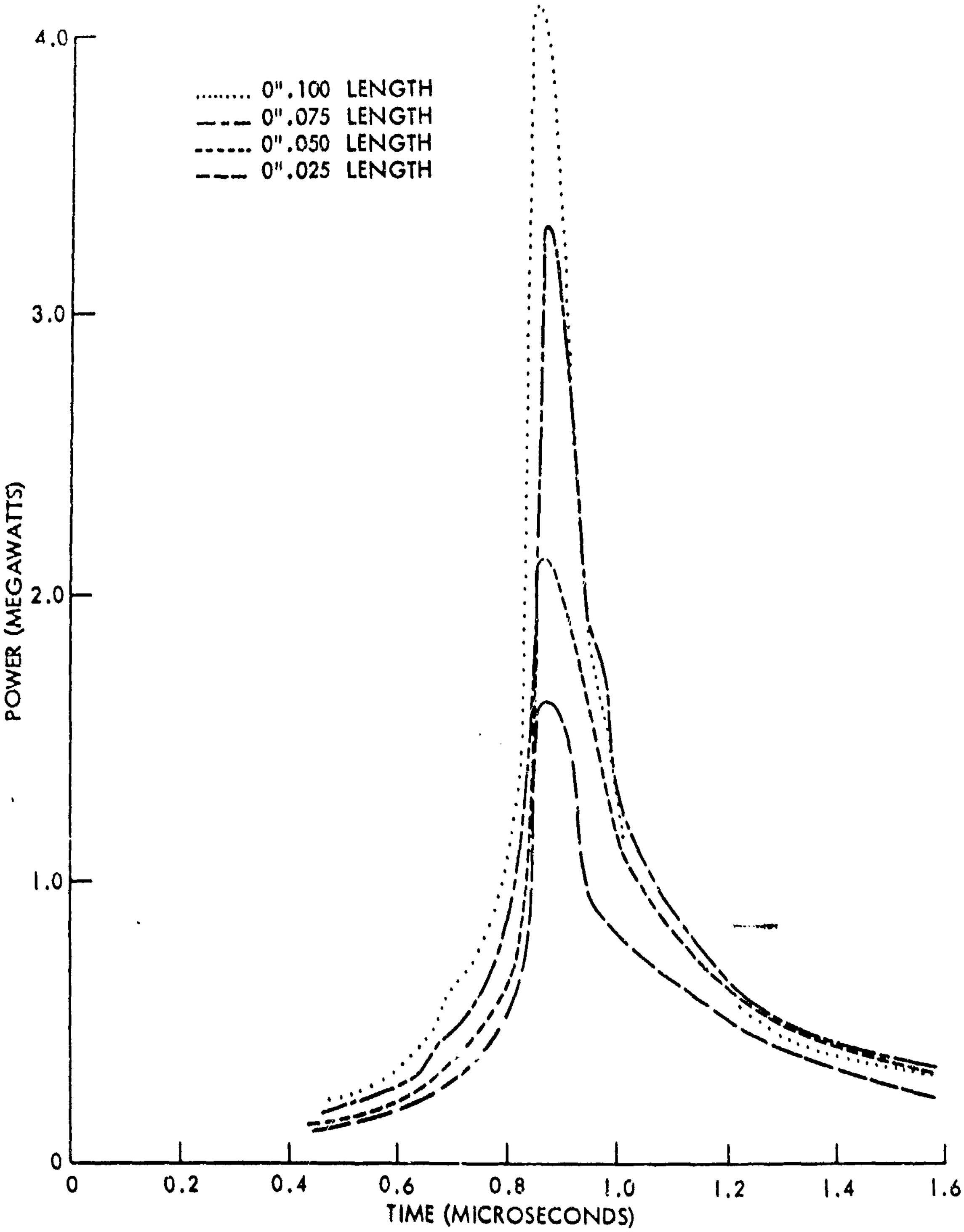

FIG. 12 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER COPPER WIRE

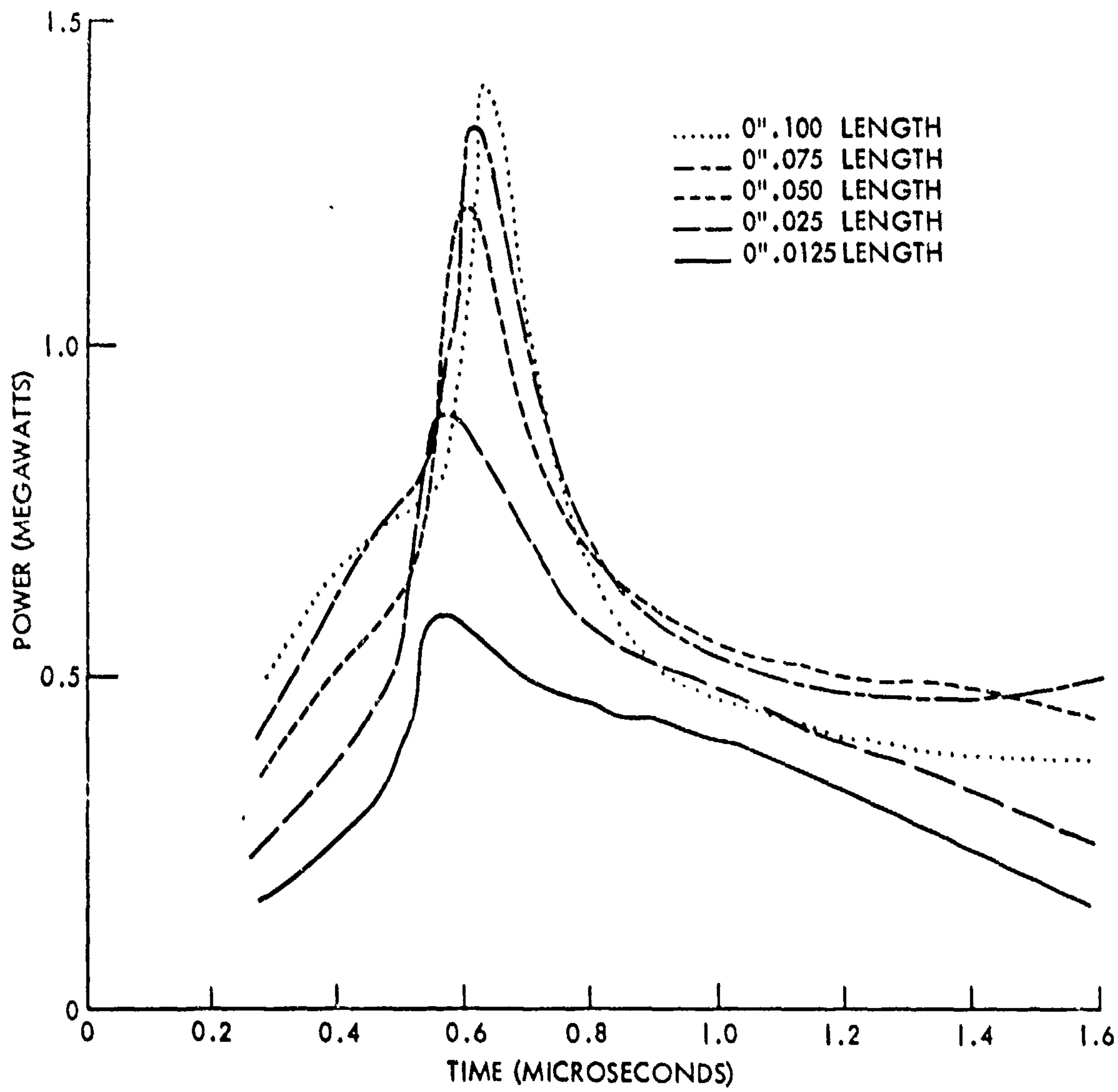

FIG. 13 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER IRON WIRE

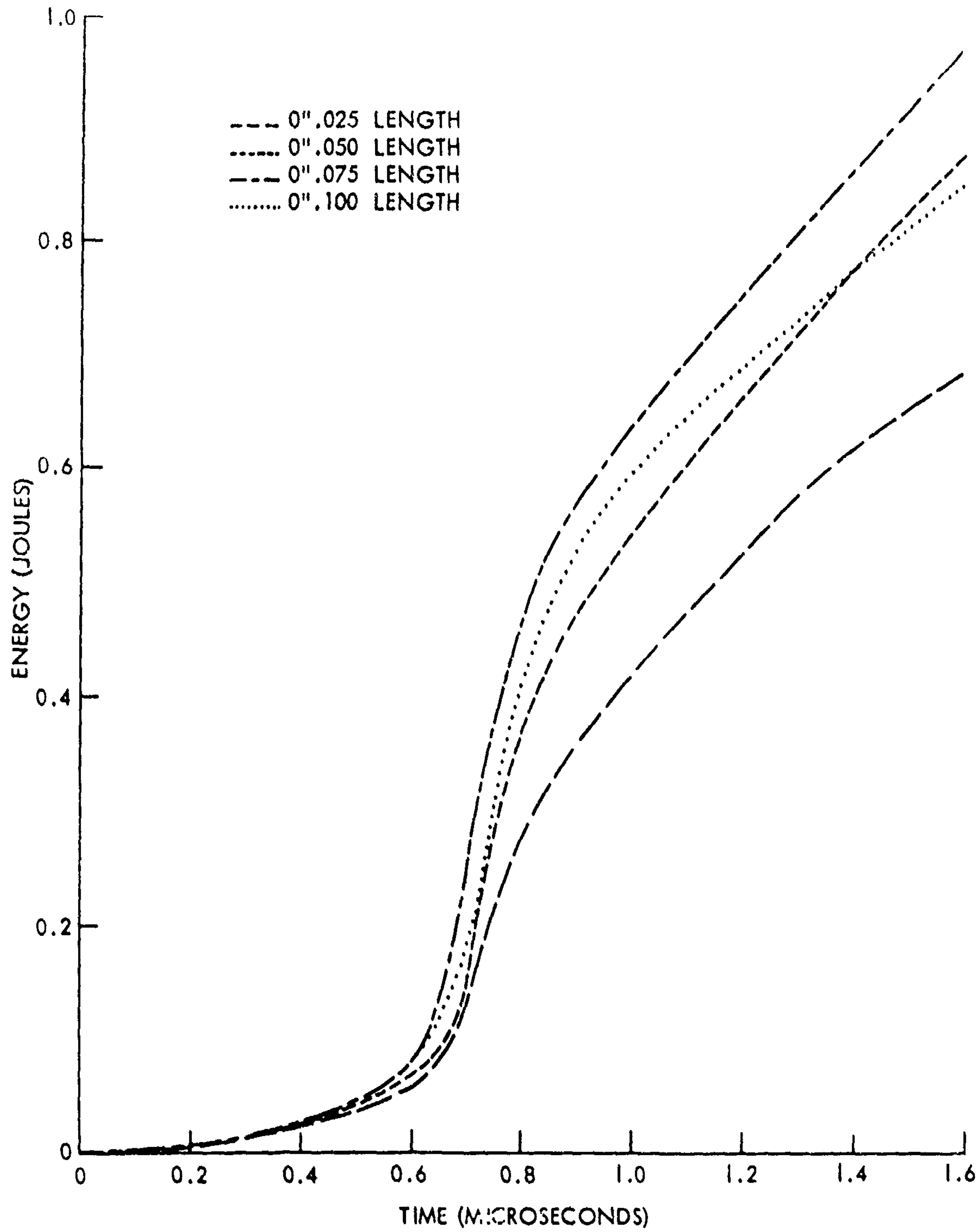

FIG. 14 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH SILVER WIRES

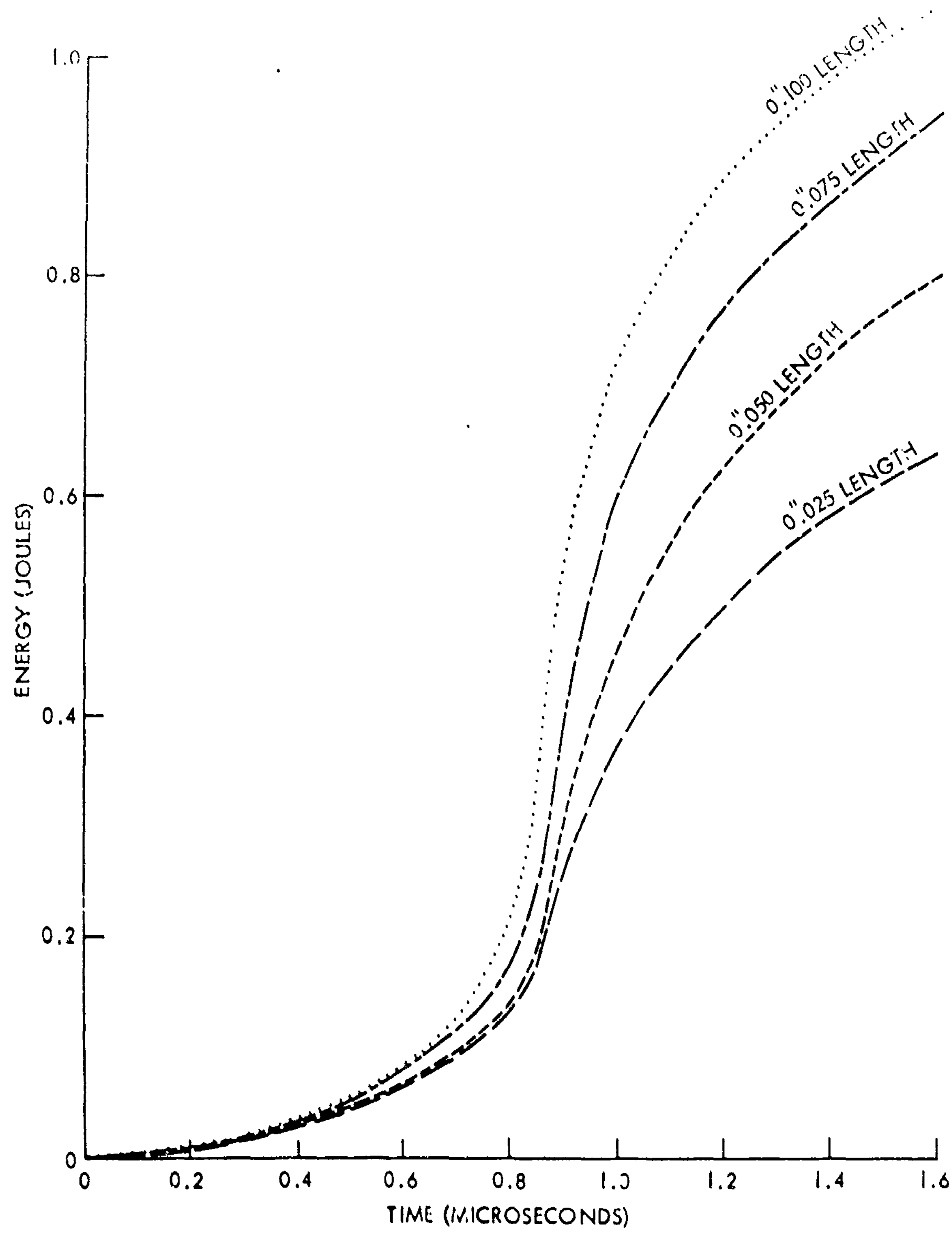

FIG. 15 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH COPPER WIRES

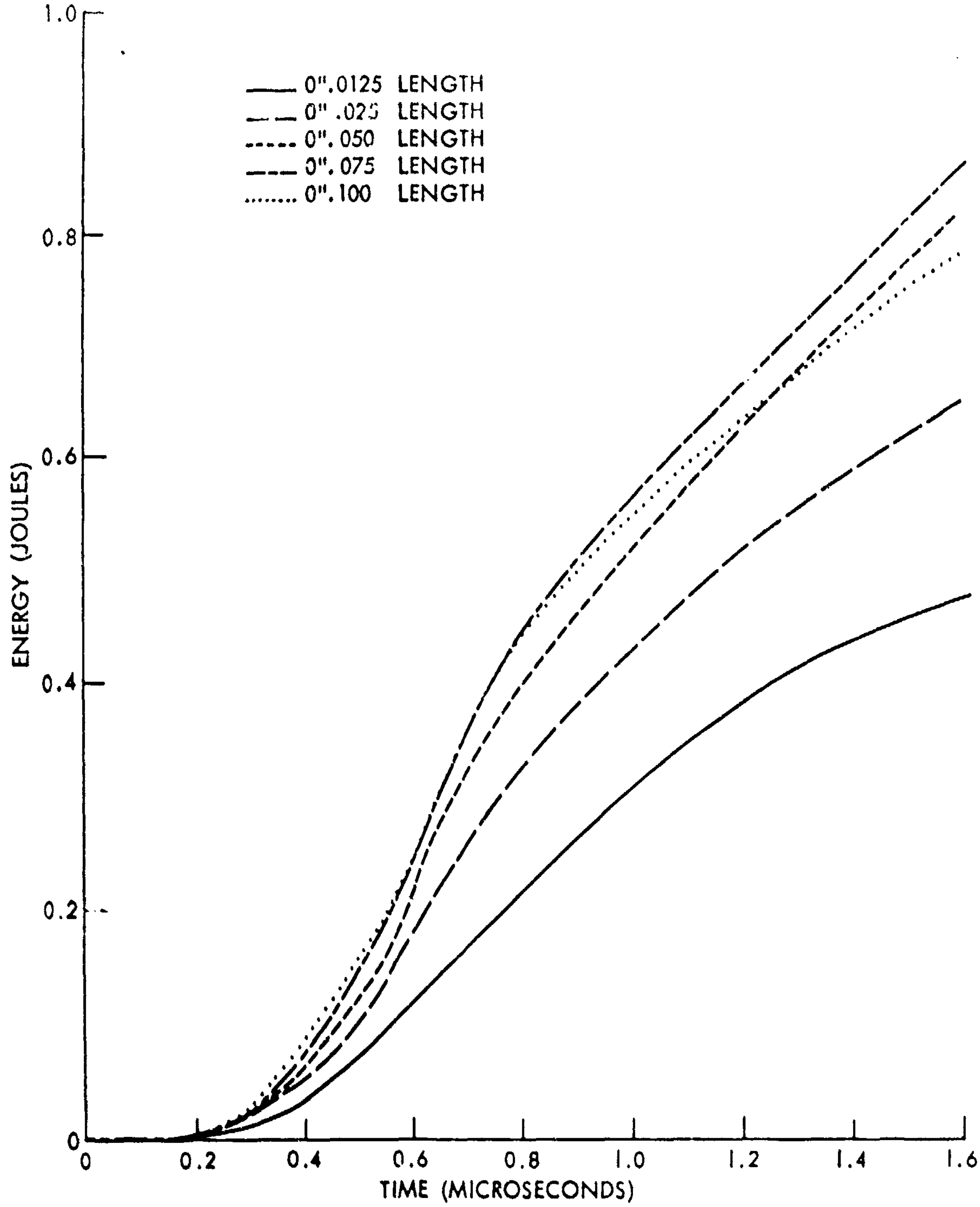

FIG. 16 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH IRON WIRES

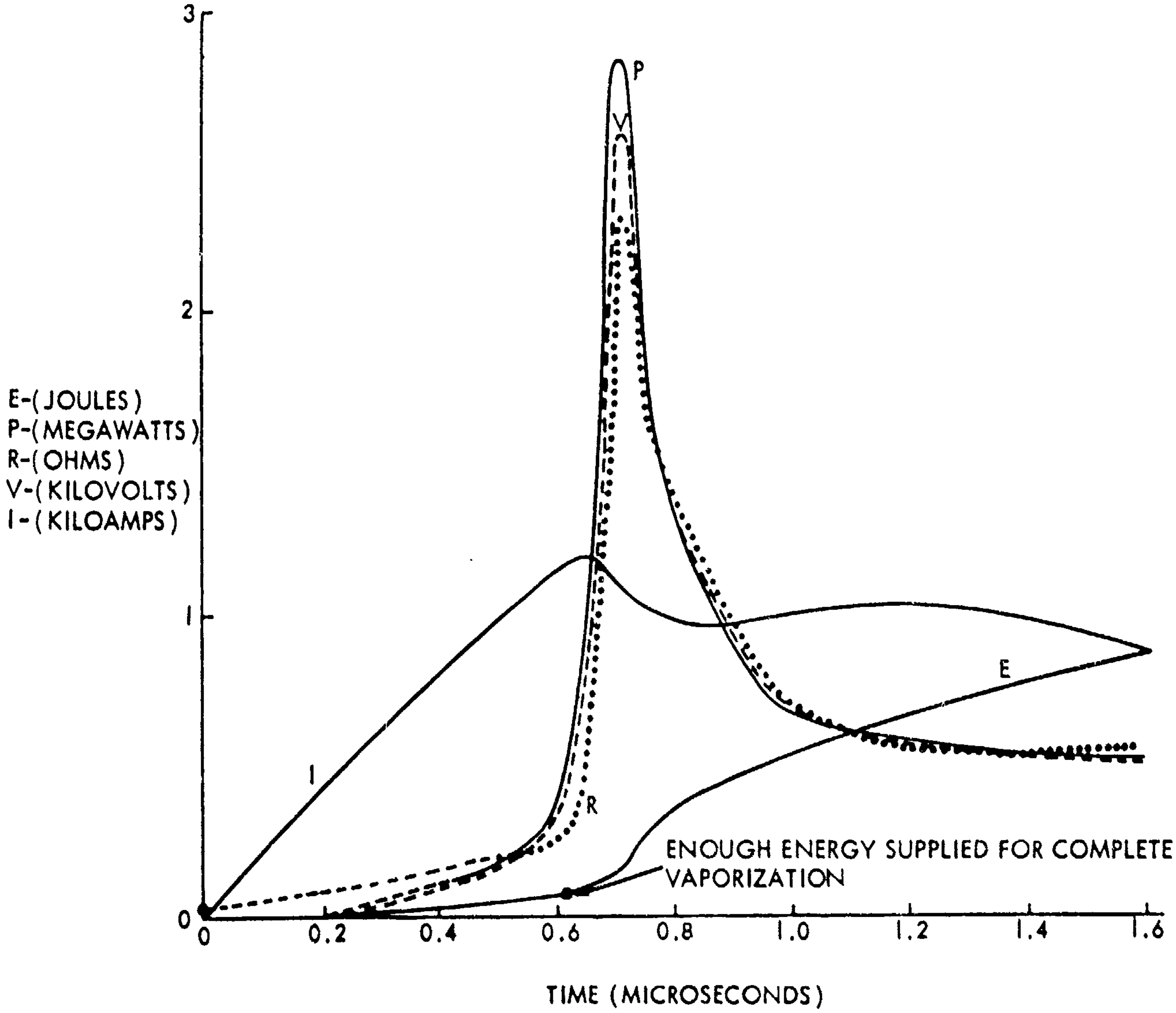

FIG. 17 COMPOSITE TRACES FOR A 2-MIL DIAMETER, 0.050-INCH LENGTH SILVER WIRE IN EXPLOSIVE TEST FIXTURE

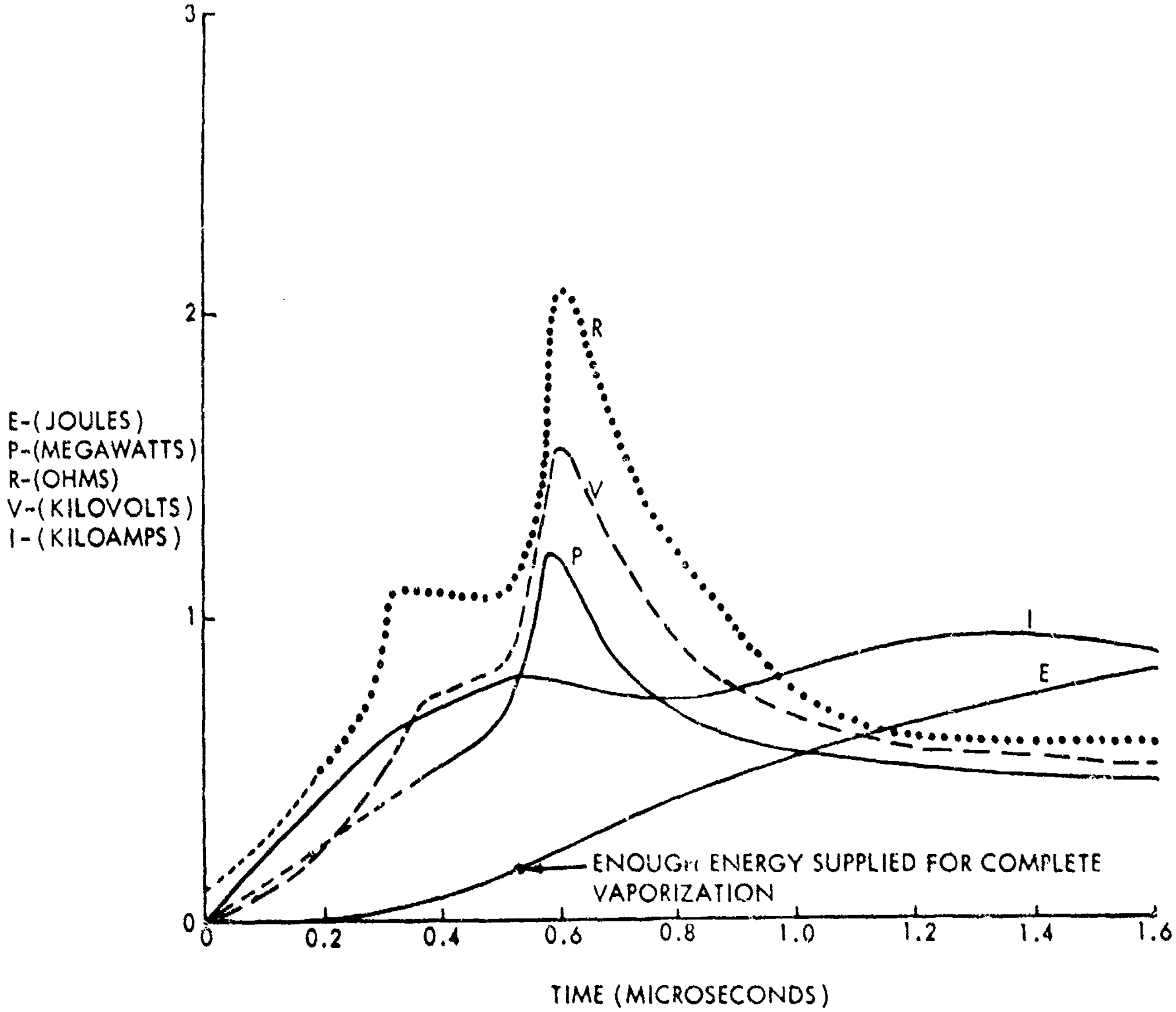

FIG. 18 COMPOSITE TRACES FOR A 2-MIL DIAMETER, 0.050-INCH LENGTH IRON WIRE IN EXPLOSIVE TEST FIXTURE

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Silver, copper, and iron wires were investigated as possible bridgewire materials. The wires were exploded by a 1-microfarad capacitor charged to 2,000 volts. Peak power input to the bridgewire is relatively more important than the energy required for vaporization. Low boiling point, low heat of vaporization metals such as silver and copper permit greater energy transfer to an explosive than high boiling point, high heat of vaporization metals such as iron.

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